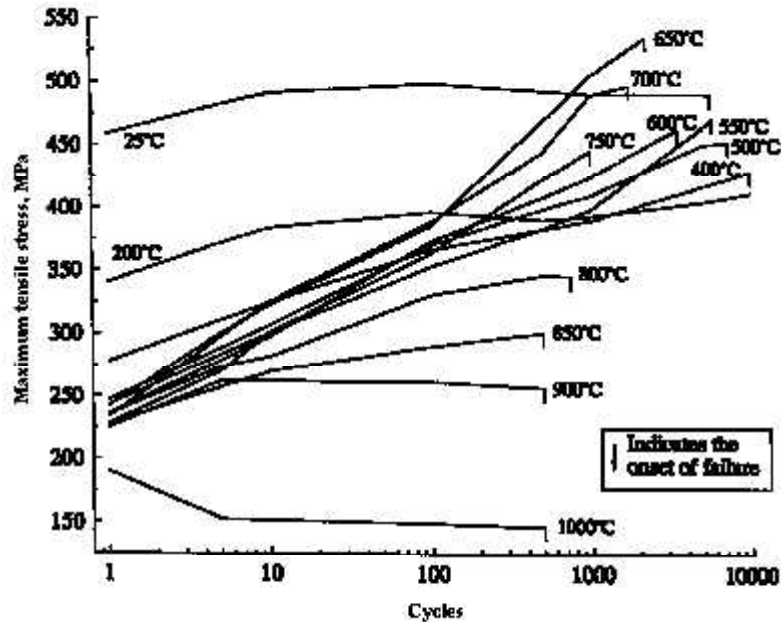


# **Temperature-Dependent Effects on the Mechanical Behavior and Deformation Substructure of Haynes 188 Under Low-Cycle Fatigue**

The mechanical behavior of a cobalt-nickel-chromium-tungsten superalloy, Haynes 188, is being critically examined at the NASA Lewis Research Center. This dynamic, strain-aging (DSA) alloy is used for combustor liners in many military and commercial aircraft turbine engines and for the liquid oxygen posts in the main injectors of the space shuttle main engine. Its attractive features include a good combination of high monotonic yield and tensile strength, and excellent fabricability, weldability, and resistance to high-temperature oxidation for prolonged exposures.

One of the current research activities on Haynes 188 is investigating the effects of temperature on the mechanical behavior and deformation substructure under low-cycle fatigue (LCF) conditions over a range of temperatures between 25 and 1000 °C at a constant strain rate of  $10^{-3} \text{ sec}^{-1}$ . Particular attention is being given to the effects of DSA on the stress-strain response and the low-cycle fatigue life. Although DSA occurs over a wide temperature range between 300 and 750 °C, the microstructural characteristics and the deformation mechanisms responsible for DSA vary considerably and depend on temperature. Furthermore, DSA is not consistently evidenced by serrated yielding or jerky flow, as is commonly exhibited in DSA alloys; however, specialized tests where the strain rate is changed at specific cycles reveal a negative strain rate sensitivity, which is indicative of DSA. A correlation between the cyclic deformation behavior and the microstructural processes is shown by detailed transmission electron microscopy investigations on material tested at various temperatures.



*Cyclic stress response of Haynes 188 under low-cycle fatigue conditions with a strain range of  $\pm 0.4$  percent and a strain rate of  $10^{-3} \text{ sec}^{-1}$ .*

As shown in the figure, Haynes 188 exhibits a relatively complex temperature-dependent stress response. At temperatures below 300 °C, the material exhibited a slight period of cyclic hardening followed by an extended period of essentially stable stress response until the onset of failure. Here, cyclic deformation occurred by simultaneous activation of two slip systems. In the midtemperature regime from 400 to 750 °C where DSA occurs, the material exhibited marked cyclic hardening prior to the onset of failure. In this regime, two slip systems were also activated, with the deformation substructure exhibiting much higher dislocation densities than those revealed at 300 °C and below. Between 650 and 750 °C, dislocations were distributed more homogeneously and were pinned by fine chromium-rich carbides, leading to enhanced cyclic hardening. Above approximately 800 °C, the tendency for cyclic hardening declined, displaying cyclic softening at temperatures above 900 °C. At 900 °C and above, dynamic recovery by thermally activated climb became prominent and lead to the formation of cells and subgrains.

The crack initiation and propagation modes also were temperature dependent in Haynes 188 under low-cycle fatigue conditions. At temperatures lower than 600 °C, crack initiation and propagation occurred in a transgranular mode. In the range between 650 and 750 °C, crack propagation occurred by a mixed transgranular plus intergranular mode, despite the fact that the crack initiation occurred by transcrystalline mechanisms. For specimens fatigued above approximately 800 °C, the fracture surfaces were covered with a thick oxidation layer. At these relatively high temperatures, the apparent predominant mechanism for crack initiation and propagation was environmentally assisted intergranular cracking.